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Drifter observations of the effects of shoals and tidal-currents on wave evolution in San Francisco Bight

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ABSTRACT

Detailed observations of wave evolution and wave–current interaction in tidal inlets and river mouths are practically non-existent. This is in part due to the practical difficulty of installing and maintaining fixed instruments in this harsh environment with large waves, strong currents, dynamic seabed morphology, and often busy ship traffic, but also due to the fact that it is difficult to resolve the spatial variability and evolution of the wave and current field from an array of point measurements. This work explores the use of newly developed small, free-drifting buoys to collect wave and current measurements in a coastal inlet. The instruments, referred to as wave-resolving drifters (or WRD), are small and lightweight enough so that they can be deployed and retrieved from small vessels, and relatively inexpensive so that large numbers can be used. The surface-following drifters resolve the three-dimensional wave orbital motion and surface current field by combining GPS and accelerometer measurements. We validate the WRD platform and its sensor package in open ocean conditions in Monterey Bay by comparing the WRD observations to observations made by a collocated 40 cm-diameter Datawell Waverider buoy. To study wave evolution in the San Francisco Bight, 30 WRDs are deployed near the San Francisco Bay entrance (Golden Gate) during peak ebb tide so that the drifters flow out of the bay, and into the incident wave field. Wave statistics are estimated through local ensemble averaging of drifter observations, and ensemble-averaged wave spectra are used to capture the wave evolution through the inlet area. Comparisons with numerical simulations of the simulating waves near shore (SWAN) model help identify the various processes acting on different frequency ranges of the wave field, and ray diagrams show the distinct effects of refraction by variable depth on the lower-frequency swells and refraction by currents on the higher-frequency wind waves. This combined analysis demonstrates the potential of using relatively inexpensive surface-following drifters to investigate surface dynamics in a complicated and energetic coastal inlet.

1. Introduction

In coastal areas characterized by strong currents and energetic waves, such as in and near tidal inlets, in situ measurements of waves and currents are very difficult to make. In particular, the use of standard measurement techniques, using bottom-mounted or moored instruments, is complicated due to e.g., the distortion of buoy response by current drag on mooring lines (Anctil et al., 1993, Steele, 1997 and De Vries et al., 2003), burying of instruments by dynamic seabed morphology (e.g. Barnard et al., 2006), and loss or damage of instruments by ship traffic (Elias et al., 2012). Moreover, waves and currents generally undergo strong spatial variations in coastal inlets and this spatial evolution and inhomogeneity is difficult to capture with a limited number of fixed instruments. As a consequence, synoptic observations of wave–current interaction and wave evolution in such regions are extremely rare, which hampers progress in understanding these dynamics in natural inlets.

In the present work we explore the use of instrumented drifters to resolve wave–current interactions in the approaches to and in a coastal inlet. Such free-drifting instruments can be readily deployed in these environments and, when used in large numbers, can provide synoptic information on the variability of waves and currents in the area of interest. The observations are Lagrangian (not Eulerian), and in regions with strong currents and

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spatially variable wave fields, recorded time series can be highly non-stationary (even if the wave conditions are fairly stationary from an Eulerian point of view). However, by deploying a large number of drifters, reliable statistical estimates can be obtained through ensemble averaging of statistical quantities estimated from short time series of nearby drifter measurements.

In the past, GPS drifters have been used extensively to measure ocean currents and surf zone dispersion (MacMahan et al., 2009), but recent advances in GPS technology have made it possible to simultaneously collect both wave and current measurements, even with inexpensive GPS receivers (Herbers et al., 2012). Although the absolute position accuracy for inexpensive off-the-shelf GPS receivers is somewhere between 2.5 m and 10 m, these errors fluctuate on time scales much longer than the periods of wind waves and swell and thus do not significantly affect wave measurements (Herbers et al., 2012). Moreover, Doppler velocity measurements, which are also available on most GPS receivers, are far less sensitive to so called "jumps" when satellites enter and leave the useable horizon. As a consequence, using the Doppler velocities rather than positions, generally results in cleaner signal and better resolution over short time intervals, which can be particularly important in the wind wave band (Thomson, 2012).

The drifters developed in this study utilize the Doppler velocity measurements from the same GPS receivers (Locosys GT-31) as those used by Herbers et al. (2012), but the sensor package is augmented with an accelerometer to resolve vertical motions and higher-frequency waves. By resolving both the horizontal and vertical wave orbital motions, we remove a 180° ambiguity in directional estimates based on horizontal GPS measurements alone (see Herbers et al., 2012), and enable the accurate measurement of strongly nonlinear waves (e.g., near breaking and steep waves on opposing currents).

The objective of the present work is twofold. The first objective is to validate the improved drifter sensor package in a natural (random) wind wave field. In particular we test the ability of the new motion sensor package, combining the GPS and accelerometer measurements, to resolve vertical motions at higher frequencies than was possible with the drifters used in Herbers et al. (2012). This is an important improvement, which will greatly enhance the potential of these drifting buoys for wave observations. We test this new capability by deploying drifters alongside a Datawell Waverider buoy in relatively homogenous open ocean conditions, and compare the frequency and directional spectra of the different buoys.

The second objective is to use the drifters (WRDs) to study wave evolution in a natural inlet, thus exploring their use in regions characterized by strong currents, and develop a reliable analysis technique that can be used to investigate the physical processes that drive wave evolution in a tidal inlet. To this end, and to observe the interactions of wind waves and swell with strong opposing currents, we deployed an array of WRD during ebb currents in the San Francisco Bight (Fig. 1) to observe the interactions of wind waves and swell with strong opposing currents. The nonstationary nature of the data records, caused by the rapid transit of the drifters through the channel and over the ebb tidal shoal, complicates the analysis. Here we show that robust estimates of wave spectra and bulk statistics can be obtained from these records by ensemble averaging short-time estimates over many drifters. Additionally, ray diagrams and simulations from a SWAN wave model, one-way coupled with a Delft3D FLOW model, were used to identify the physical mechanisms responsible for the changes in the wave field in the approaches to and in the tidal inlet as seen in the drifter observations.

We describe the field experimental site and drifter sensor package design in Section 2. The wave–current model implementation is outlined in Section 3, and the observed wave evolution is compared to model predictions in Section 4. Finally, we summarize our findings in Section 5.

2. Field site and instrumentation

2.1. Field site

The San Francisco Bay is a large tidal estuary that is connected to the Pacific Ocean by a narrow inlet. The bay side (east) of the inlet is spanned by the Golden Gate Bridge at the narrowest point, and the west side of the inlet opens to the Pacific Ocean (see Fig. 1). A mixed semi-diurnal tide and a 28-day spring and neap cycle (NOAA – National Oceanic and Atmospheric Administration, 2009) results in strong tidal forcing through the inlet where the current speeds can exceed 2.5 ms^{-1} near the inlet mouth and maintain velocities in excess of 1 ms^{-1} to the ebb tidal shoal approximately 8 km offshore (Barnard et al., 2006; Elias et al., 2012; and Barnard et al., 2012). Waves approaching the San Francisco Bight from a predominantly WNW direction interact with a complex shoal area bathymetry and a strong ebb tidal jet (Elias and Hansen, 2012 and references therein).

2.2. Wave resolving drifters (WRD)

The drifters developed and used in this study were designed as lightweight instrument packages that can be deployed from small vessels and accurately resolve both ocean surface waves and currents. The drifter itself consists of a 30 cm diameter, hard shell, closed-cell foam core buoy (Jim-Buoy model 4400-RF) with a 1.25 cm wide rubber band attached near the waterline to mitigate the immersion buoyancy resonance that occurs at 1.11 Hz for this drifter. A ballast weight (10.4 kg) is suspended from a shackle to submerge the buoy approximately to the centerline (see Fig. 1).

The wave–current sensor package attached to the buoy consists of a GPS receiver (Locosys GT-31), and a three-axis accelerometer package (Gulf Coast Data Concepts X6-2). The latter is tethered between the buoy and the ballast chain (Fig. 1) to maintain a nearly vertical orientation of the accelerometer, irrespective of the buoy orientation, and thus suppress the sensitivity to roll and pitch motions of the buoy vertical acceleration measurements that can result from steeper, high-frequency waves.

To allow real-time tracking of the drifter's position, which is essential as a recovery aid when deploying large numbers of drifters close to shore in strong currents, the drifter is equipped with a Garmin DC 40 GPS transmitter.

2.2.1. GPS position and velocity sensor

The Locosys GT-31 GPS receiver, based on the SIRF III chipset, collects data at 1 Hz and accurately resolves the horizontal components of the wave orbital displacements using differential position data (see Herbers et al., 2012). Additionally, estimates of horizontal velocity can be extracted from the Doppler shifts in the raw L1 carrier phase signals. The resolution of the Doppler velocity data is an order of magnitude higher than the differential positioning data, which particularly improves the accuracy of high-frequency wind–wave measurements (Thomson, 2012). In this experiment both horizontal Doppler velocity and differential positions were recorded and analyzed.

Herbers et al. (2012) show that the GT-31 sensors yield accurate and reliable wave energy and direction spectra. However, vertical